PILOT USE IN ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING BASED SPREAD SPECTRUM MULTIPLE ACCESS SYSTEMS

Sub A

Related Application

United States Patent application Serial No. (R. Laroia-J. Li-S. Rangan-P. Viswanath Case 15-8-4-1) was filed concurrently herewith.

Technical Field

This invention relates to communications systems and, more particularly, to orthogonal frequency division multiplexing (OFDM) based spread spectrum multiple access (SSMA) systems.

Background of the invention

It is important that wireless communications systems be such as to maximize the number of users that can be adequately served and to maximize data transmission rates, if data services are provided. Wireless communications systems are typically shared media systems, i.e., there is a fixed available bandwidth that is shared by all users of the wireless system. Such wireless communications systems are often implemented as so-called "cellular" communications systems, in which the territory being covered is divided into separate cells, and each cell is served by a base station.

It is well known in the art that desirable features of cellular wireless communications systems are that intracell interference be as small as possible and that intercell interference be averaged across all users in adjacent cells.

In such systems, it is important that mobile user units are readily able to identify and synchronize to the downlink of a base station transmitting the strongest signal. Prior arrangements have transmitted training symbols periodically for mobile user units to detect and synchronize to the associated base station downlink. In such arrangements, there is a large probability that the training symbols transmitted from different base stations would interfere with each other. Indeed, it is known that once the training symbols interfere with each other they will continue to interfere. Thus, if the training symbols are corrupted, then the data is also corrupted, thereby causing loss in efficiency. Pilots that are randomly placed in the time-frequency grid might not solve this problem too.

Summary of the Invention

Problems and/or limitations of prior base station identification and downlink synchronization arrangements are addressed by employing pilot signals including known symbols transmitted at prescribed frequency tones in individual ones of prescribed time intervals. Specifically, the symbols used in the pilots are uniquely located in a time-frequency grid, i.e., plane, where the locations are specified by periodic pilot tone hopping sequences.

In a specific embodiment of the invention, a period of a pilot tone hopping sequence is constructed by starting with a Latin-square based hopping sequence, truncating it over time, and optionally offsetting and permuting it over frequency. Particular examples of pilot tone hopping sequences are parallel slope hopping sequences in which the periodicity of the sequences is chosen to be a prime number of symbol time intervals.

In another embodiment of the invention, a notion of phantom pilots is employed to facilitate use of various system parameters while accommodating the above noted pilot tone hopping sequences. That is, based on system considerations, when the frequency range of the above generated pilot tone hopping sequences exceeds the available bandwidth of a particular system a problem results. This problem is overcome by truncating the pilot tone hopping sequences whenever the tone frequency exceeds the bandwidth, that is, designating these tones as phantom pilot tones and not transmitting them.

Brief Description of the Drawing

FIG. 1 illustrates a frequency domain representation in which a prescribed plurality of tones is generated in a prescribed bandwidth;

FIG. 2 illustrates a time domain representation of a tone f_i;

FIG. 3 is a graphical representation of a time-frequency grid including a pilot tone hopping sequence;

FIG. 4 is another graphical representation of a time-frequency grid including other pilot tone hopping sequences;

FIG. 5 shows, in simplified block diagram form, details of a transmitter including an embodiment of the invention;

FIG. 6 shows, in simplified block diagram form, details of a transmitter including another embodiment of the invention;

FIG. 7 is another graphical representation of a time-frequency grid illustrating phantom tone regions; and

FIG. 8 illustrates a multicell environment in which the invention may advantageously be employed.

Detailed Description

FIG. 1 illustrates a frequency domain representation in which a prescribed plurality of tones is generated in a prescribed bandwidth. In this example, bandwidth W is employed to generate a total of N_t tones, i.e., $i=1,\ldots N_t$. The tones are spaced at $\Delta f=1/T_s$ apart, where T_s is the duration of an OFDM symbol. Note that the tones employed in this embodiment of the invention are generated differently than those generated for a narrow band system. Specifically, in a narrow band system the energy from each tone is strictly confined to a narrow bandwidth centered around the tone frequency, whereas in an Orthogonal Frequency Division Multiplexing (OFDM) system that is a wide band system the energy at a particular tone is allowed to leak into the entire bandwidth W, but it is so arranged that the tones do not interfere with one another.

FIG. 2 illustrates a time domain representation of tone f_i within symbol period T_s. Again, note that within each symbol period T_s, data may be transmitted on each of the tones substantially simultaneously.

FIG. 3 is a graphical representation of a time-frequency grid, i.e., plane, including a pilot tone hopping sequence. In general, a pilot tone includes known waveforms that are transmitted from a base station so that mobile receivers can estimate various parameters, for example, channel coefficients. In an Orthogonal Frequency Division Multiplexing based Spread Spectrum Multiple Access (OFDM-SSMA) system, in accordance with an aspect of the invention, the pilots include known symbols transmitted at prescribed frequencies and prescribed time instances. Indeed, OFDM systems employ orthogonal tones within a prescribed frequency bandwidth to transmit data to a plurality of users at the same time. Example pilot tones are shown in the lined regions of the time-frequency grid in FIG. 3. As shown, the pilots, i.e., tones, are located in the time-

frequency grid in a parallel slope pilot tone hopping sequence. The use of pilot tones in the parallel slope pilot tone hopping sequence reduces the search effort of mobile user units in the process of base station identification and downlink synchronization. In the example shown in FIG. 3 there is one pilot tone hopping sequence having a prescribed slope "a"= 2, and the periodicity of this sequence is five (5) symbol intervals, i.e., T=5. Therefore, in this example, during each symbol interval, a distinct pilot tone is employed, and over one sequence period of T symbols, p distinct pilot tones are employed. In this example we have $p = T$, but in general this is not necessary. The tones are numbered along the frequency axis and the symbol intervals, i.e., periods, are numbered along the time axis of FIG. 3. Thus, as shown, during: symbol interval (1), pilot tone (2) is transmitted; symbol interval (2), pilot tone (4) is transmitted; symbol interval (3), pilot tone (1) is transmitted; symbol interval (4), pilot tone (3), is transmitted; and during symbol interval (5), pilot tone (5) is transmitted. Thereafter, the pilot tone hopping sequence is repeated.

In summary, if the spacing between tones in FIG. 3 is $\triangle f$ then:

tone 1 corresponds to f;

tone 2 corresponds to $f + \triangle f$;

tone 3 corresponds to $f + 2\triangle f$;

tone 4 corresponds to $f + 3\triangle f$;

tone 5 corresponds to $f + 4\triangle f$.

Similarly, if the duration of a symbol interval is T_s then:

time 1 corresponds to t_0;

time 2 corresponds to $t_0 + T_s$;

time 3 corresponds to $t_0 + 2T_s$;

time 4 corresponds to $t_0 + 3T_s$;

time 5 corresponds to $t_0 + 4T_s$;

time 6 corresponds to $t_0 + 5T_s$;

time 7 corresponds to $t_0 + 6T_s$.

FIG. 4 is another graphical representation of a time-frequency grid including other pilot tone hopping sequences. In the example shown in FIG. 4 there are two pilot tone

hopping sequences represented by "X" and "O". Each of the pilot tone hopping sequences shown in the example of FIG. 4, has a prescribed slope "a" and a periodicity of five (5) symbol intervals, i.e., T=5. Therefore, in this example, during each symbol interval, two distinct pilot tones are employed, and over one sequence period of T symbols, p distinct pilot tones are employed for each of the two pilot tone hopping sequences. In this example we have $p = T$. The tones are numbered along the frequency axis and the symbol intervals, i.e., periods, are numbered along the time axis of FIG. 4. Thus, as shown, during: symbol interval (1), pilot tones (2) and (4) are transmitted; symbol interval (2), pilot tones (1) and (4) are transmitted; symbol interval (3), pilot tones (1) and (3) are transmitted; symbol interval (4), pilot tones (3) and (5) are transmitted; and during symbol interval (5), pilot tones (2) and (5) are transmitted. Thereafter, the pilot tone hopping sequences are repeated.

FIG. 5 shows, in simplified block diagram form, details of a transmitter including an embodiment of the invention. Specifically, shown are pilot tone hopping sequence generator 501 and pilot waveform generator 502. Pilot tone hopping sequence generator 501 generates pilot sequences that specify tones to be used by the pilot at any time instant. Note that each cell uses N_{pil} pilot sequences. The pilot sequence is defined as $S_i = \{f_0^{S_i}, f_1^{S_i}, \cdots f_k^{S_i}, \cdots\}$, for $i = 1, \cdots N_{pil}$. The pilot sequence is supplied to pilot waveform generator 502 that generates, in this example, a waveform represented by $\sum_{i=1}^{N_{pil}} C_k^{S_i} e^{2\pi f_k^{S_i} \Delta f t}$ that, in turn, is supplied to antenna 503 for transmission after modulating a carrier frequency. Note that Δf is the basic frequency spacing between adjacent tones, $C_k^{S_i}$ is a known symbol to be transmitted at the k^{th} symbol instant and tone $f_k^{S_i}$.

In this example, a Latin Square based pilot hopping tone sequence is generated by $f_k^{s_i} = Z\{(a(k \bmod T) + s_i) \bmod p + d\}$, where "k" is a time instant index, "T", "a", "s_i" and "d" are integer constants, "p" is a prime constant, "Z" is a permutation operator defined on [MIN (0, d), MAX ($N_t - 1, p - 1 + d$)] and "N_t" is the total number of tones in the system. The parameter "T" is periodicity in time of the pilot tone hopping sequence. The parameter "d" is chosen such that $0 \le d \le N_t - p$. This choice of "d" ensures that the pilot tone hopping sequence lies within the transmission bandwidth.

Further note that in this example, "p" is a prime number, is constant for all cells in the system, and is close to N_t. Also in this example, "Z" is an identity mapping. That is, any tone is mapped to itself, i.e., $Z\{f\} = f$. This particular choice for Z simplifies mobile unit receiver processes for synchronization and identification of the pilot of a base station, and improves the quality of channel estimation. Additionally, a small deviation from the identity mapping by appropriately defining Z may preserve some of the above salient features. However, such an arrangement is still covered by the general expression of permutation operator Z noted above. Moreover, Z is the same for all cells. The choice of $T = p$ ensures that a period of the tone hopping sequence is the same as a Latin square hopping sequence and in combination with the choice of Z as an identity mapping results in the generation of the parallel slope tone hopping sequences. Other choices of T that are close to p would result in slight deviations from parallel slope tone hopping sequences. Parameter "a", i.e., the pilot hopping sequence slope, varies from cell to cell. This is illustrated in FIG. 8 below in an example including three (3) cells having parameters, i.e., slopes, a_1, a_2 and a_3, respectively. N_{pil}, $\{S_1,\cdots S_{N_{pil}}\}$, is such as to provide a sufficient number of pilot tones for channel estimation. N_{pil} is the same for all cells. Finally, $\{S_1,\cdots S_{N_{pil}}\}$ is such as to enable the pilot functionalities, such as, channel estimation, base station identification and frame synchronization.

As alluded to above, use of pilot tones serves several roles in cellular communication systems. For example, they are employed to identify a new base station and the one having the strongest transmission signal, synchronize in both time and frequency to the strongest transmitting base station, and facilitates downlink channel estimation. By using above formula for $f_k^{S_i}$ with $T = p$ the maximum number of collisions of the pilot tone hopping sequences of two neighboring base stations is minimized. Moreover, by choosing Z to be an identity mapping, the pilots generated are several parallel slope pilot tone hopping sequences, as shown in FIG. 4. The use of so-called slope pilots reduces the search effort in the process of base station identification and downlink synchronization. The value of the slope, the spacing between the parallel slopes and the number of pilot tone hopping sequences are determined based on a variety of considerations including channel estimation and base station identification. The

physical layer frame size is chosen to be one period of the pilot tone hopping sequence. This facilitates tracking of so-called physical layer frames. Furthermore, a very uniform distribution of the pilot symbols is realized in that there is a fixed number transmitted in every symbol time and the pilot sequences are readily computable at a mobile unit receiver. In another embodiment of the invention, the notion of phantom pilots is employed to facilitate use of various system parameters while accommodating the above design of pilot tone hopping sequences. That is, based on system considerations, the frequency range of the pilot tone hopping sequences noted above exceeds the available bandwidth of a particular system, which would be a problem. This problem is overcome by truncating the pilot tone hopping sequences whenever the tone frequency exceeds the bandwidth, that is, designating these tones as phantom pilot tones and not transmitting them.

The concept of phantom tones facilitates a flexible choice for various system design parameters while accommodating the above design of pilot tone hopping sequences. The number of tones into which a certain bandwidth can be divided into depends on parameters of the system, such as, the data rate to be supported on each individual tone and the length of a cyclic prefix that is required to be used to ensure orthogonality in a multipath environment. Based on such considerations, an N_t that is smaller than p may be arrived at for the system, which is a problem. The problem being that the pilot tone hopping sequence generated sometimes exceeds the allowable bandwidth. For certain choices of d this problem exists even if N_t is greater than or equal to p. This problem is resolved by employing the notion of phantom tones. That is, a prime number "p" is selected that is larger than N_t. Then, the pilot tone hopping sequences are generated using p by assuming that we have a bandwidth of p tones. $(p - N_t)$ of these tones are called phantom tones. These tones are called phantom tones because they are not transmitted. The number of pilot tone hopping sequences is chosen to ensure that the channel estimation requirements are satisfied in spite of the phantom tones that are not transmitted. Indeed, the use of phantom tones has minimal adverse impact on the base station identification and synchronization processes.

FIG. 6 shows, in simplified block diagram form, details of a transmitter that employs phantom tones in accordance with another embodiment of the invention. The elements in FIG. 6 that are essentially identical to those shown in FIG. 5 have been similarly numbered and are not described again in detail. The difference between the transmitter 500 of FIG. 5 and transmitter 600 of FIG. 6 is that so-called phantom pilot tones generated by sequence generator 501 are not included in the waveform generated by pilot waveform generator 601. Thus, waveform generator 601 during the k^{th} symbol instant, provides the waveform $\sum_{i=1}^{N_{pil}} C_k^{S_i} \Gamma_k^{S_i} e^{2\pi f_k^{S_i} \Delta f t}$, where, as above, Δf is the basic frequency spacing between adjacent tones, $C_k^{S_i}$ is a known symbol to be transmitted at the k^{th} symbol instant and tone $f_k^{S_i}$, and $\Gamma_k^{S_i} = 1$, if $f_k^{S_i} \in [0, N_t - 1]$, and $\Gamma_k^{S_i} = 0$, otherwise.

FIG. 7 is another graphical representation of a time-frequency grid illustrating phantom tone regions. As shown in FIG. 7, pilot tones generated by pilot tone sequence generator 501 are not transmitted if they fall within the phantom tone regions, namely, [MIN (*0, d*), *0*] and [$N_t - 1$, MAX ($N_t - 1, p - 1 + d$)].

FIG. 8 illustrates a multicell environment in which the invention may advantageously be employed. Thus, shown are neighboring cells 801, 802 and 803 each having a pilot tone hopping sequence slope associated with it, namely, slopes a_1, a_2 and a_3, respectively. The slopes a_1, a_2 and a_3 are each unique to their associated cell 801, 802 and 803, respectively. It should be understood, however, that some distant cell may employ a slope such as either a_1, a_2 or a_3 so long as the particular remote cell does not interfere with the local cell employing the same slope for the pilot tone hopping sequence.

A mobile user unit, i.e., cell phone or the like, that may utilize the pilot tone hopping sequence arrangement of this invention to identify a base station is described in United States Patent application Serial No. (R. Laroia-J. Li-S. Rangan Case 15-8-4), filed concurrently herewith and assigned to the assignee of this application

The above-described embodiments are, of course, merely illustrative of the principles of the invention. Indeed, numerous other methods or apparatus may be

devised by those skilled in the art without departing from the spirit and scope of the invention.